GaN and GaAs High Power Process Research Leads to Advances for Military Applications

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I. Introduction

Gallium nitride technology has been under development since the late 1990s. This developmental process grew from small pieces being studied in universities and advanced research labs into a viable technology sought for military applications including airborne phased array radar, SatCom and electronic warfare. Both private and governmental funding have propelled research and development in this wide bandgap material to bring it to market at a faster rate than was realized by gallium arsenide in the 1970s and 1980s.

Most of the RF transistor work to date has been done on HEMTs (high electron mobility transistors). There continues to be work done on heterojunction bipolar transistors (HBTs), but these devices lag HEMT development by several years and face some formidable challenges before they become commercially viable, hence the focus on HEMT GaN devices for military systems.

Interest in gallium nitride (GaN) for military applications stems from several advantages including intrinsic material qualities that allow for transistor designs capable of handling higher voltage levels. Gallium nitride has much higher power capability compared to gallium arsenide due to its high breakdown voltage and high current. In addition, gallium nitride has been demonstrated to have good noise and linearity characteristics, making it suitable for a wide range of applications.

Higher input voltage enables higher power at a given frequency. Higher voltage / higher power are attractive to military systems designers because GaN-based circuits can perform at a given level using fewer individual devices. In addition, device sizes can be reduced. With sufficiently high efficiency, fewer and smaller circuits would also produce less waste heat which is advantageous for a number of reasons.

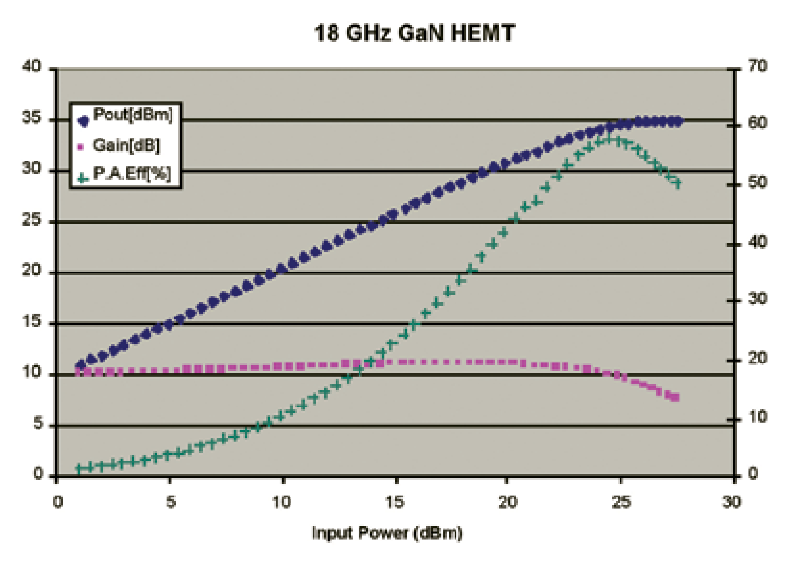

Figure 1: Power, gain and efficiency for TriQuint 400 micron GaN HEMT unit cell indicating the exceptional performance TriQuint has achieved in developing high frequency devices in Phase II of its DARPA contract.

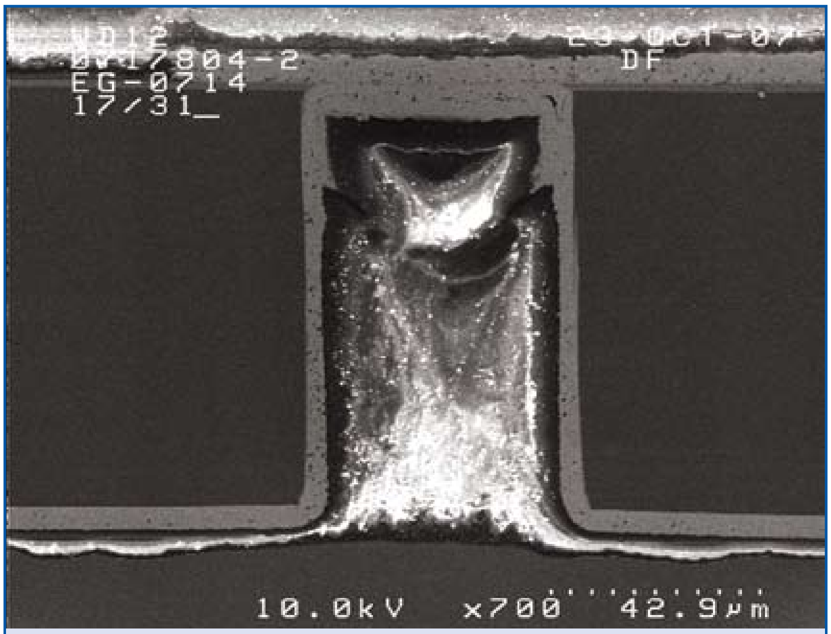

Figure 2: This scanning electron microscope image shows a cross section of the through-substrate via, a critical feature of TriQuint's high frequency gallium nitride (GaN) MMIC process. The use of vias for circuit grounding is a critical feature for high performance GaN integrated circuits

TriQuint Semiconductor has been a leader in Gallium Nitride HEMT development. It began investigating GaN along with university and commercial partners in 1999. By 2001, TriQuint had established a baseline process using 2-inch material on its R&D line in Richardson, Texas. The process showed promising results with over 7W/mm and efficiency as high as 50% at X-band, but the material and process were still immature.

In 2003, TriQuint was the first to apply an integrated field plate gate and achieved stable, high efficiency devices operating at 30V. TriQuint established a baseline field plate process on its Richardson manufacturing line and in late 2004, 3-inch material started to become widely available. In 2005 TriQuint was selected by DARPA (Defense Advanced Research Projects Agency) to lead a multi-year research and development effort into 100W GaN devices suitable for military and commercial applications.

TriQuint is now in year three of the five year DARPA program, successfully completing Phase II and expecting to enter Phase III, which extends performance goals for MMIC development and to demonstrate that performance in a GaN module. The goals of the Phase III wide band track are to demonstrate a 100W decade wide module covering X-band with 25% module efficiency and over 30dB module gain. Accomplishments since 2005 included employing a dual field plate technology in 2006, which together with improved substrate materials enabled stable, reliable 40V operation with efficiency over 60%; power density over 6.4W/mm and gain over 12dB at X-band were also achieved. Further refinements demonstrated highly superior results at 30GHz and 35GHz. In 2007 the team overcame the fact that some devices produced earlier in the program degraded rapidly under test. Materials and process improvements led to exceptional advances and more repeatable power performance. After three years in the program, the team has been able to achieve repeatable, high-yielding, high-performance devices with long life times.

TriQuint has also been pursuing alternate substrates for gallium nitride. Work with GaN on silicon began in 2003.

Researchers demonstrated excellent MMIC results at S- and X-band. Impressive power results were recently demonstrated with GaN on Si load pull at 30GHz. In 2007, TriQuint started working with GaN on diamond to explore a relatively low cost, high thermal conductivity substrate. TriQuint demonstrated transistors in early 2007 using this material and continues to work on alternate substrates with industry partners in 2008.

While much development energy has been directed toward gallium nitride, TriQuint has also created new high voltage gallium arsenide pHEMT (pseudomorphic high electron mobility transistor) processes. At the 2008 GOMACTech conference in Las Vegas, TriQuint reported results on three. The first, a product-released 0.35µm PWRPHEMT process, was developed to support frequencies up to 18GHz at a drain bias of 12V. At 10GHz and under 12V operation this process achieves 1.6W/mm and 60% PAE. This is about 33% higher power density compared to conventional 0.25µm PWRPHEMT. This new, higher voltage process technology has supported high power applications across multiple military programs.

II. Military Systems and Gallium Nitride

Due to the high power characteristics of GaN, high power saturated amplifiers for the military were among the first applications envisioned. The government funded development at universities, followed by DARPA and the services laboratories supporting advanced gallium nitride research at semiconductor manufacturers.

The military application range for GaN is from L-band up to W-band. At lower frequencies, from L-band through C-band, gallium nitride has some formidable competition from silicon carbide, silicon LDMOS, and high voltage gallium arsenide. These technologies are well suited for lower frequency applications and in some cases JUNE be more cost effective. These technologies are further along in their respective life cycles and are hence available sooner for application development. However, gallium nitride's cost and maturity will continue to improve, opening the possibility that it will be competitive at a point in these markets.

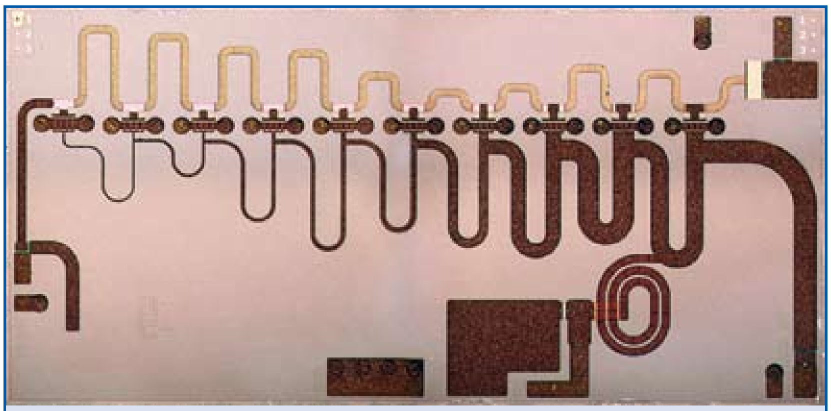

Figure 2: Experimental gallium nitride wideband power amplifier shown in close-up

The advantages of GaN over other technologies in the high power amplifier (HPA) market intensify at higher frequency. Silicon carbide and silicon LDMOS devices cannot perform at X-band and high voltage gallium arsenide becomes less compelling as frequency increases. This is because operating voltage and frequency are traded-off. For GaN, however, this trade-off does not come until much higher frequencies. GaN is capable of operating at very high voltages through X- and Ka-bands with commensurate power levels while maintaining high efficiency. More compact amplifiers can be built operating at higher system voltages which in turn lowers overall system cost, decreases overall system dimensions and at sufficiently high efficiency and where applicable can reduce waste heat and extend battery life.

GaN's advantages are probably at their peak over competing technologies at Ka-band to Q-band. GaN is capable of many times more power density in frequency bands that have been starved for power in solid state. Most high power applications in this range are still using tube-based power amplifiers. These are expensive, bulky and not very reliable. Military customers have been trying to eliminate TWT (traveling wave tube) amplifiers for a long time now, but have not been very successful with GaAs solid state devices. Gallium nitride's high power and efficiency at Ka- and Q-band make it likely to succeed in toppling the traveling wave tubes.

The wide bandgap of GaN also offers high input protection capability for low noise amplifiers. Very good noise figures have been measured and reported on GaN devices. Increased stand off voltage means that input limiter diodes can either be reduced or eliminated, reducing loss in the receive chain and improving overall system performance. DARPA has been funding X-band low noise amplifiers under the WBGS-RF program.

III. Gallium Nitride Strategy

TriQuint expects to offer 40V gallium nitride products and foundry service starting in 2008. The GaN process will offer three levels of metal interconnect similar to gallium arsenide foundry processes. More development is underway to offer gallium nitride for higher frequency applications and higher voltage, low frequency markets. As the industry moves to 4" material, TriQuint is ready to ramp-up volume on its production manufacturing line and has already pursued goals of the Phase II GaN development program using 4-inch substrates.

Government and service laboratories, as well as DARPA, are focusing their GaN development work on high frequency applications, including W-band, which spans roughly 70 to 110 GHz and can be used for communications, radar and non-lethal weapons systems. To achieve the high frequency operation, transistor gate dimensions are shrunk to 100nm or below and epitaxial layers are scaled appropriately. Operating voltage is typically less than 20V, but still much higher than available today from indium phosphide or metamorphic HEMTs operating at 1.5 to 2.5V.

TriQuint has chosen to focus initial development in the 2-20GHz range as it enables coverage of the majority of military and commercial market applications at which the higher manufacturing and production costs of GaN are mitigated by significantly improved performance. Gallium nitride serves as a baseline technology from which to push higher in frequency for millimeter wave markets and higher in voltage for low frequency markets.

IV. Summary

As an emerging technology, gallium nitride is being rapidly developed for both military and commercial applications. Its high power and efficiency make it ideal for power amplifiers ranging from L-band to W-band. By reducing material costs and converting to 4-inch wafers, gallium nitride will become even more competitive in commercial markets. Through the dedicated efforts of researchers at TriQuint Semiconductor and partner companies and universities working as part of the DARPA multi-year GaN development program, repeatable, high-yielding and high-performance devices with long life times have been achieved. These achievements open the door to next-generation advances in military phased array radar, communications and electronic warfare development activities. At the same time that advances are being heralded in high frequency gallium nitride work, TriQuint has extended the capabilities of conventional gallium arsenide pHEMT devices by developing high-power processes that yield significantly improved power density and PAE compared to conventional 0.25µm PWRPHEMT devices for military applications. The availability from TriQuint of commercial Foundry high frequency gallium nitride processes and die-level devices is expected in 2008. For more information about gallium nitride products and other high-frequency devices, register for product updates at www.triquint.com/rf.

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